Chapter 2

Theoretical Concepts of Geology

Theoretical concepts of Geology

1. THEORETICAL CONCEPTS OF GEOLOGY

1.1 General remarks

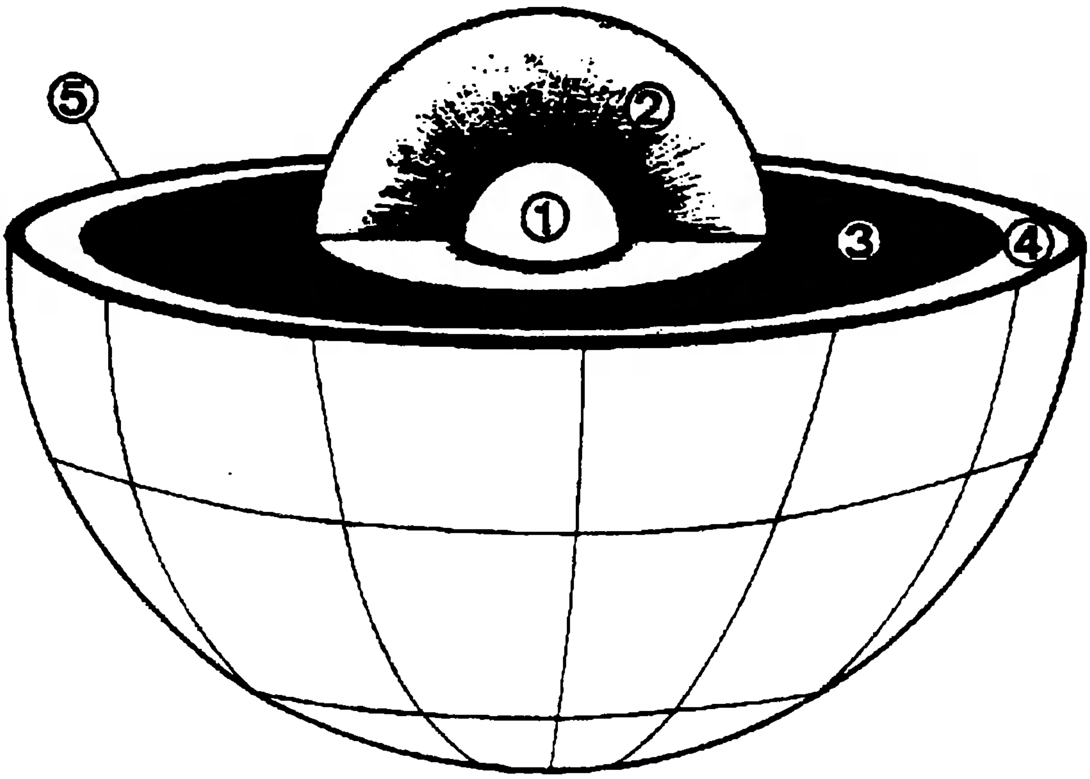
The following concepts of geology represent a very small selection of available concepts. They should illustrate how the gaps between isolated data points are filled. In a way they represent the essence of the "imagination" a geologist uses to produce a coherent geological model of a raw material deposit. These concepts are derived from observations made on the actual geological process. This ongoing process, although slow in time, can be studied and described and the results can be compared to ancient "documents" in the form of rocks.

There is also much circumstantial information used in the construction of these concepts. By using the existing examples of rock formation, one assumes that the conditions for these processes have not changed with time. This is not entirely true, since certain changes to these general conditions (like for example the polarity and the strength of the earth's magnetic field) have occurred many times in the past. Still, the so-called actualistic model is best suited to explain the features of ancient rocks.

1.2 The structure of the earth

There is enough scientific evidence to assume that the earth consists of a series of zones (Fig. 1) which differ distinctly from on another other in their chemical and physical characteristics. The earth's center is a solid core of nickel and iron, surrounded by a zone of liquid material (liquid core"). The mantle lying between the core and the crust is divided into two sections: the mantle as such and the "upper" mantle. Both are chemically characterized by the abundantly present sulphur-oxygen compounds combined with heavy metals. The crust itself can be divided into two portions, the oceanic crust (Silicon, Magnesium and Iron as main elements) and the continental crust (Silicon and Alumina).

Fig.1 **Structure of the Earth**



Legend:

① solid core

② liquid core

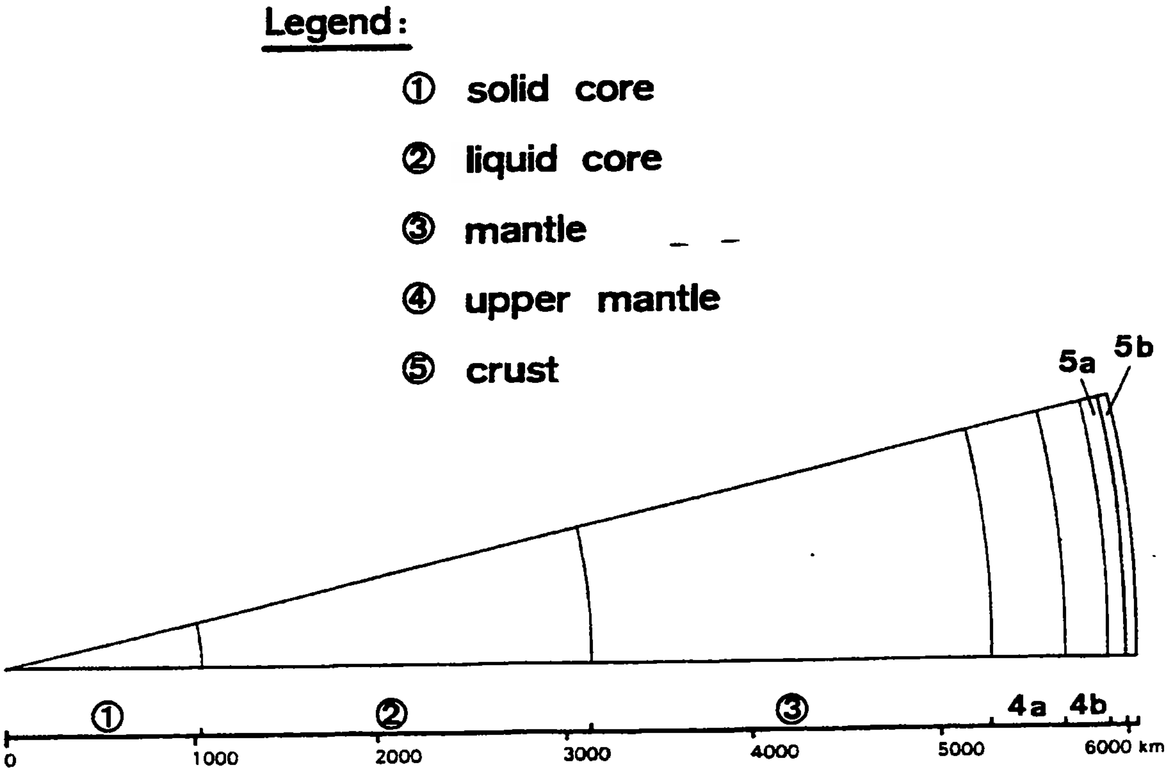
③ mantle

④ upper mantle

⑤ crust

Compared with the other structural elements of the earth, the crust is a very thin layer, of an average thickness of only 30 - 40 km (Fig. 2).

Fig.2 **Structure of the Earth**



The crust and the upper mantle together form the lithosphere, which forms a solid plate of rock of about 100 km thickness.

1.2.1 Composition of the Lithosphere

Only approx. 10 - 15 km of the lithosphere has been sufficiently investigated to permit characterization. It is astonishing that the predominant components in that portion of the lithosphere, which are accessible for industrial processing, are, oxygen (50 %) and silicon (25 %, Tables 1 and 3). The remaining 25 % are formed by eight other elements and a mere 0,8 % by the remaining 82 naturally occurring elements, many of which are technically and industrially important (Table 2).

TABLE 1: Composition of the lithosphere

O	46,6 %	
Si	27,7 %	
Al	8,1 %	91,0 %
Fe	5,0 %	
Ca	3,6 %	
Na	2,8 %	
K	2,6 %	
Mg	2,1 %	

TABLE 2: Composition of the lithosphere: minor and trace constituents

10^{-1} %	Ti, H, Mn, P
10^{-2} %	F, S, C, Cl, Rb, Sr, Ba, Zr, Cr, V, Zn
10^{-3} %	Ni, Cu, Li, N, Sn, Co, Pb, Th
10^{-4} %	As, B, Mo, Br, W, U
10^{-5} %	Sb, Bi, Ag
10^{-6} %	Hg, A
10^{-7} %	Au, Pt, He

TABLE 3: Chemical composition of the earth, the lithosphere and of Portland cement

		Earth	Lithosphere	Portland cement
Oxygen	O	22,0	46,6	37,0
Silicon	Si	11,0	27,7	9,5
Aluminium	Al	0,6	8,1	3,2
Iron	Fe	50,0	5,0	2,0
Calcium	Ca	1,0	3,6	45,3
Magnesium	Mg	9,0	2,1	1,2
Potassium	K		2,6	0,5
Sodium	Na		2,8"	0,1
Hydrogen	H		0,9	
Nickel	Ni	6,0		
Titanium	Ti		0,6	

1.2.2 Global Plate Tectonics

Based mainly on results of geophysical research done during the last 30 years (Geomagnetics, Paleomagnetics, Gravity, Seismic), an old hypothesis was confirmed beyond doubt: Continents are constantly changing their positions relative to one another, i.e. they move on the globe. Such movements were put forward in the thirties by A. WEGENER, based on the excellent fit of the coast lines of North/South America on one side, and Europe/Africa on the other side of the Atlantic Ocean. It has been found that the entire globe is actually covered by so-called "plates" that comprise the crust and the solidly crystallized part of the upper mantle (fig. 2a) (the "lithosphere"). Solid parts of this lithosphere move constantly (continental drift), and the so-called "plate boundaries" accommodate this shift.

Three types of plate boundaries are recognized:
distensive, compressive and lateral

- The distensive boundaries are those sites, where new lithosphere is created, nearly exclusively along the so-called mid-ocean ridges. Their relatively mobile liquid masses from the molten part of the upper mantle are welling up to the sea floor and crystallise to form a solid "crust". The rising magma itself segregates because of changes in pressure and temperature, as a result of which different rocks are formed at different depths. The lateral rate of accretion has been measured to be in the order of 2 to 10 cm per year.
- The compressive plate boundaries are essential for destroying parts of the crust (otherwise, the globe would expand). This is effected by thrusting slabs of oceanic crust + mantle down into the liquid part of the mantle.
  These slabs potentially reach a depth of 600 - 700 km, and they are the reason for the deep-seated earthquakes. At surface, they are marked by deep-sea trenches, volcanic arcs and mountain chains (fig. 2b).
- The lateral boundaries are expressed as large wrench faults, normally a system of near vertical faults which can accommodate lateral movements of the plates. These form the links between the other two types of plate boundaries.

Plate boundaries are naturally marked by many geological activities like earthquakes, mountain forming, rapid sedimentation, volcanism etc. The major features of these plates are well established, and a globally compatible pattern of their movements over the last 200 - 300 mio years has been worked out. In detail, however, there are still many problems pending, e.g. the problem of "microplates" or the development of "marginal basins". The descriptions thus far concerned exclusively the kinematics of the plates. The dynamics, or "the driving force", is not completely clear and still heavily contested amongst geologists. The simplest model consists of a "convection cell" mechanism. The liquid part of the mantle cools and sinks in certain areas, whereas in other places the hot molten material rises to the lithosphere (fig. 2 c). Calculations of the thermodynamics involved show that even violent convection is possible, provided the assumption of viscosities, temperatures etc. is realistic. The global plate tectonics model for the first time in the history of the science of geology explains the large geological features in a satisfactory way. Doubtless with the increasing amounts of reliable data available, the model will be modified in the future.

Fig.2a Major Plate Boundaries of the Globe

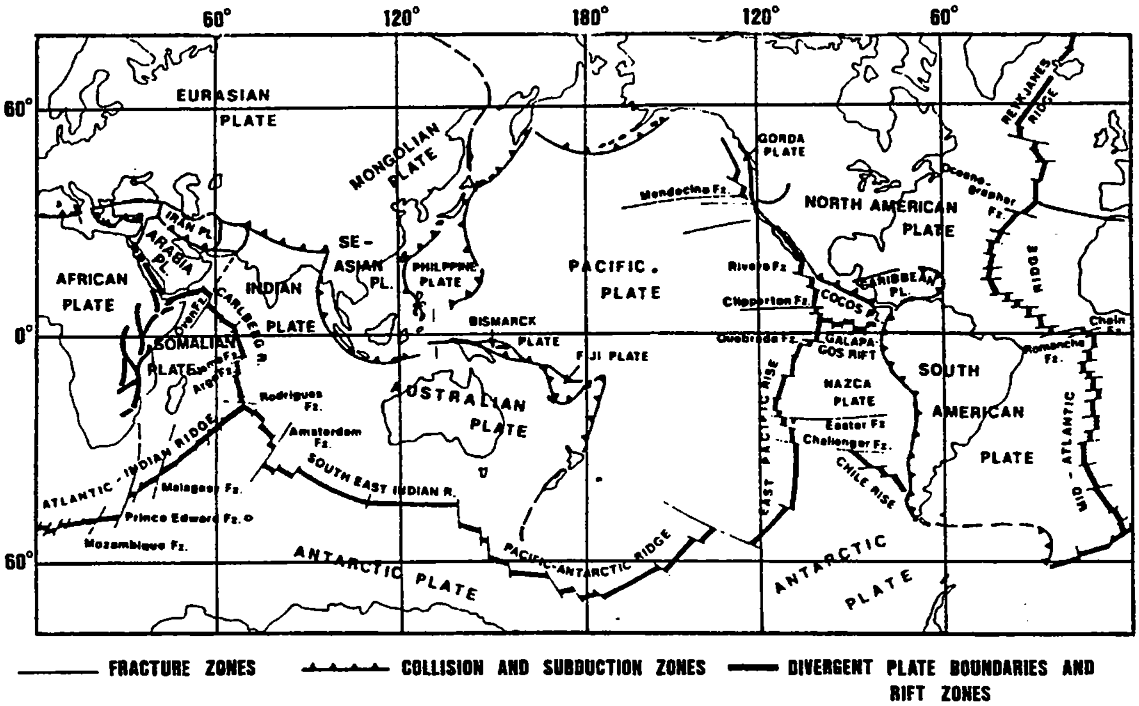


Fig.2b Compressive Plate Boundary

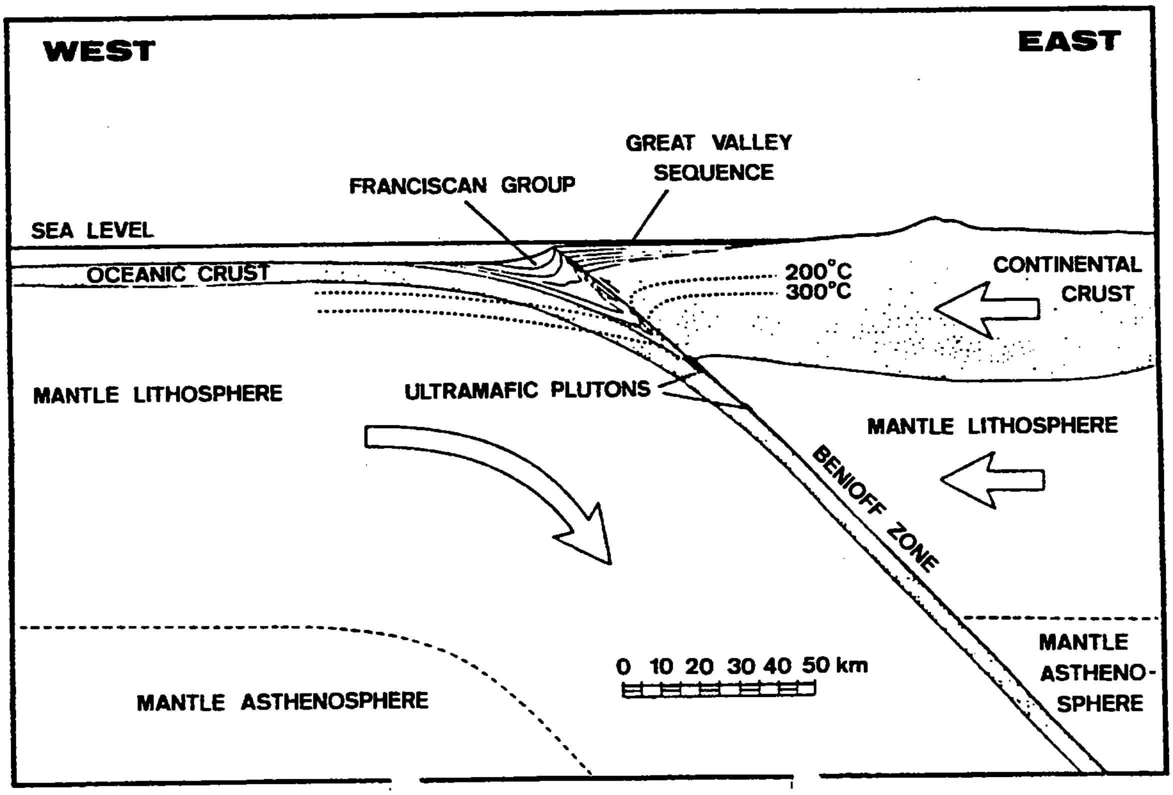
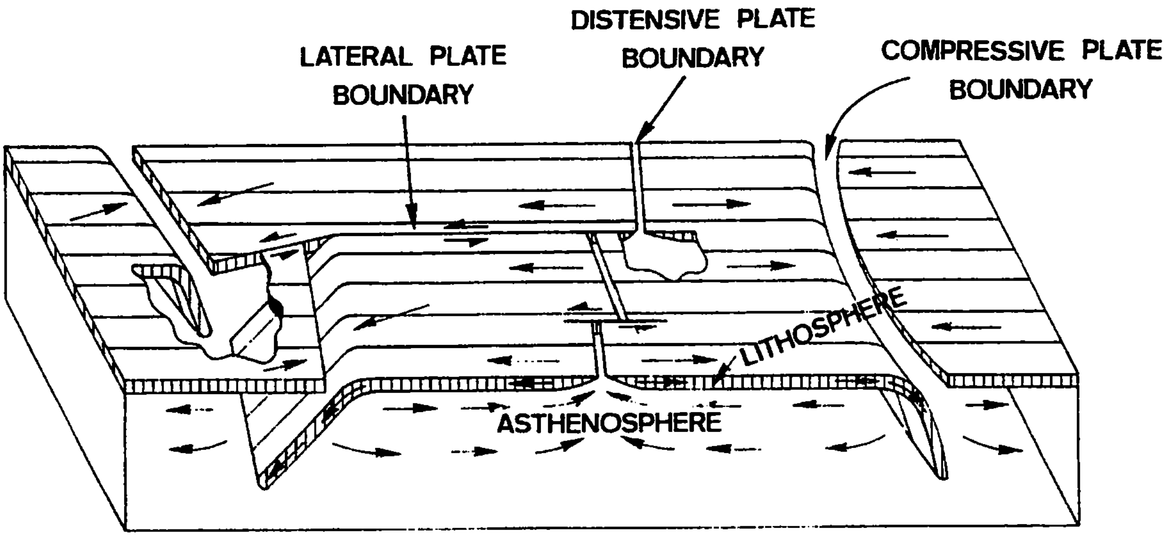


Fig. 2c Global Plate Tectonics Model



1.3 Rock Classification

1.3.1 General remarks

Rocks are classified according to the following criteria:

- mineral content
- genesis, place of formation
- age

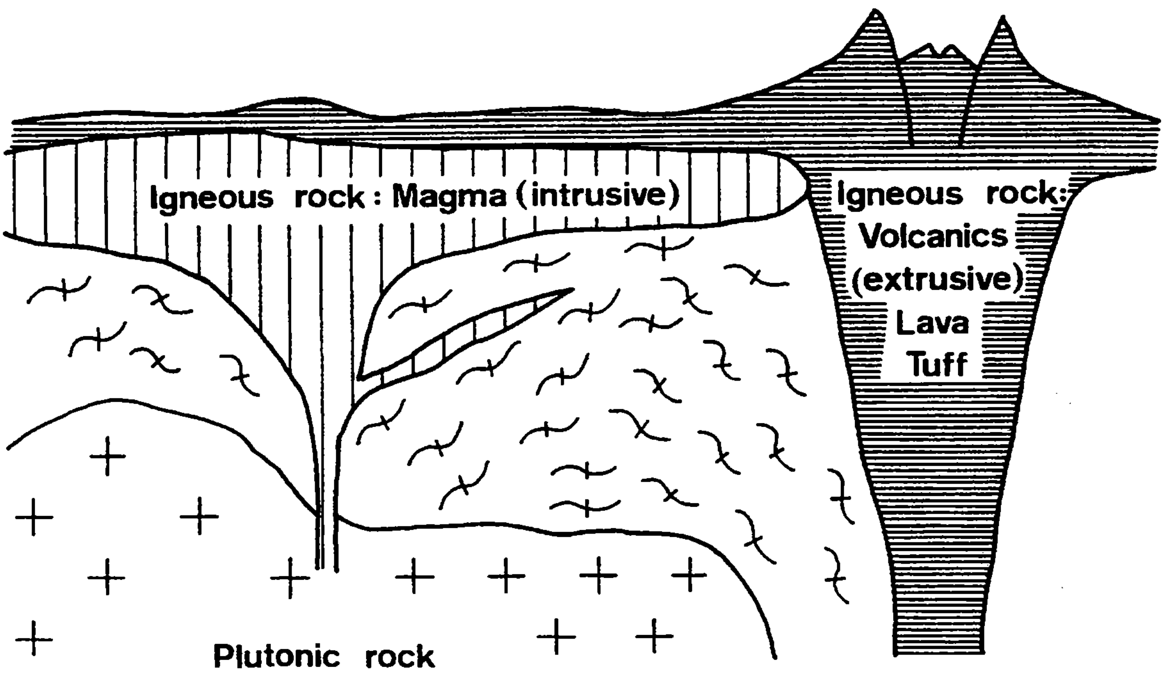
Accordingly, three large groups - each of them divided into several subdivisions - can be established:

- igneous rocks
- sedimentary rocks
- metamorphic rocks

1.3.2 Igneous Rocks (Fig. 3)

The magma, which originates from the deeper part of the globe (mostly the upper mantle), rises towards the surface and forms different types of rocks depending on its cooling history and its differentiation process. The magma can change its chemical composition by fractional crystallization and by assimilation of rock fragments of the formations it penetrates. Slow cooling of the magma leads to the development of large crystals, rapid cooling e.g. in a volcano eruption, leads to very small crystals or even amorphous matter in form of volcanic glass.

Fig.3 Igneous Rocks



Rocks of this type are often used in Cement and aggregate industry, e.g. as pozolana or crushed rock (granite, basalt), see table 4.

TABLE 4 Igneous rocks in cement and aggregate industries

Volcanics	tuff ash lava perlite agglomerate
Plutonics	granite diorite
Intrusives	andesite, basalt

1.3.3 Sedimentary Rocks

If rocks of any kind are exposed to weathering and erosion caused by temperature changes, atmospheric conditions, etc. on the surface of the earth, disintegration results. Basically, weathering includes two phenomena:

- weathering with undissolved products
- weathering with dissolved products

The formation of sediments includes the following stages

1) Disintegration of the solid rock
2) Transport of dissolved and undissolved products
3) Deposition and precipitation
4) Compaction (Diagenesis)

According to this, three types of sedimentary rocks are distinguished:

mechanical (clastics)	only mechanical action
chemical	precipitation of dissolved matter
organic	remains of living beings precipitation by organisms

Deposition occurs frequently in the form of a more or less horizontal layering called stratification (strata = layer).

Sedimentary rocks are the most significant resource for the cement and aggregate industry (Table 5). Detailed descriptions and criteria of assessment are given in section 4 "Assessment of Cement Raw Materials".

TABLE 5 Sedimentary rocks in the cement industry

chemical	limestone gypsum anhydrite ironoxihydrate aluminiumoxihydrate rock salt
mechanical	sandstone, sand marl clay, claystone shale
organic	limestone coal oil

1.3.4 Metamorphic Rocks

During rock formation, every mineral and rock is in equilibrium with its environment at a distinct pressure (P) and the temperature (T). Metamorphosis (transformation) of rocks is mostly caused by disturbance to this equilibrium. If one or both of these parameters change, metamorphosis takes place. Metamorphic rocks may, therefore, be formed from igneous as well as from sedimentary rocks, whereby the chemistry of the metamorphic rock may be virtually identical with the composition of the original rock. Metamorphic limestone (marble) is often used as a raw material in cement industries. Other metamorphic rocks are suitable as aggregates, even for special applications (e.g. amphibolite) as aggregates.

TABLE 6 Metamorphic rocks in the cement industry

Metamorphic rock	Original rock
Amphibolite	Basalt
Marble	Limestone
Phyllite	Shale
Quartzite	Sandstone
Slate *	Shale
Schist *	Shale

* inaccurate terms, to be avoided

1.4 Circuit of Geological Processes

Table 7 demonstrates the interdependence of the rock types as described previously.

The geological processes, which lead to the various types of rocks, can also be demonstrated in terms of a circuit (Fig. 4).

Fig. 4 Circuit of geological processes

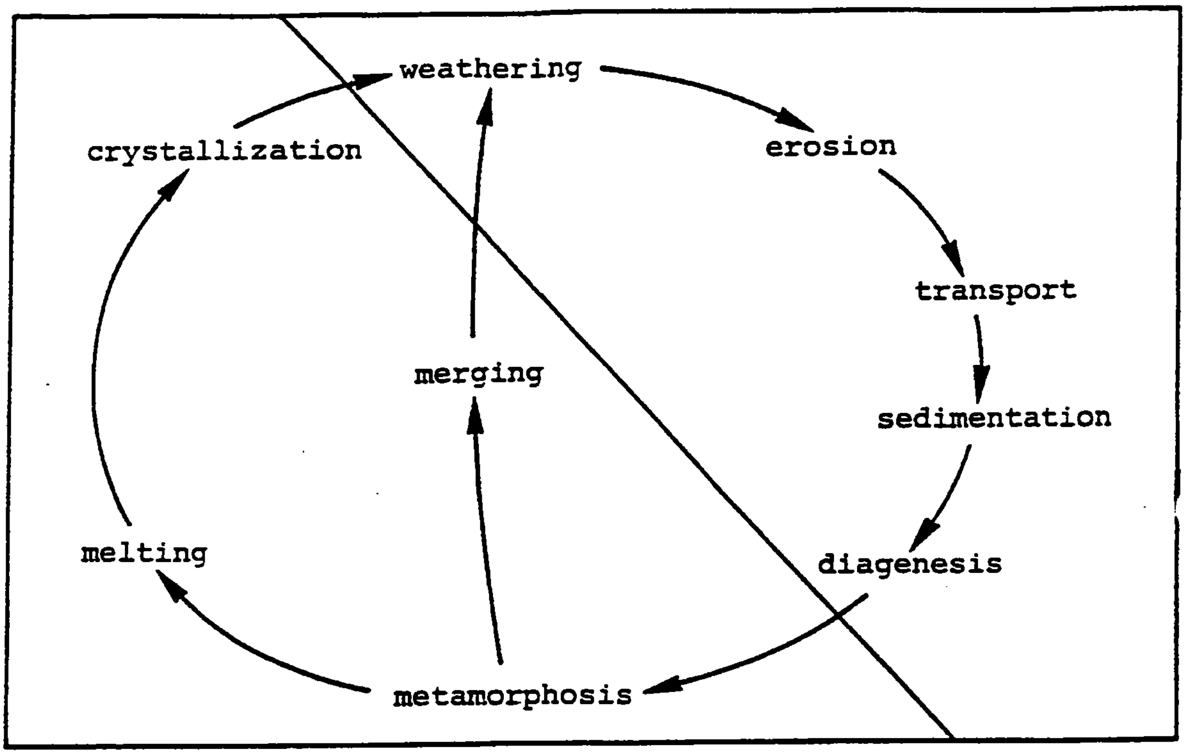


Fig. 4a **Circuit of geological processes**

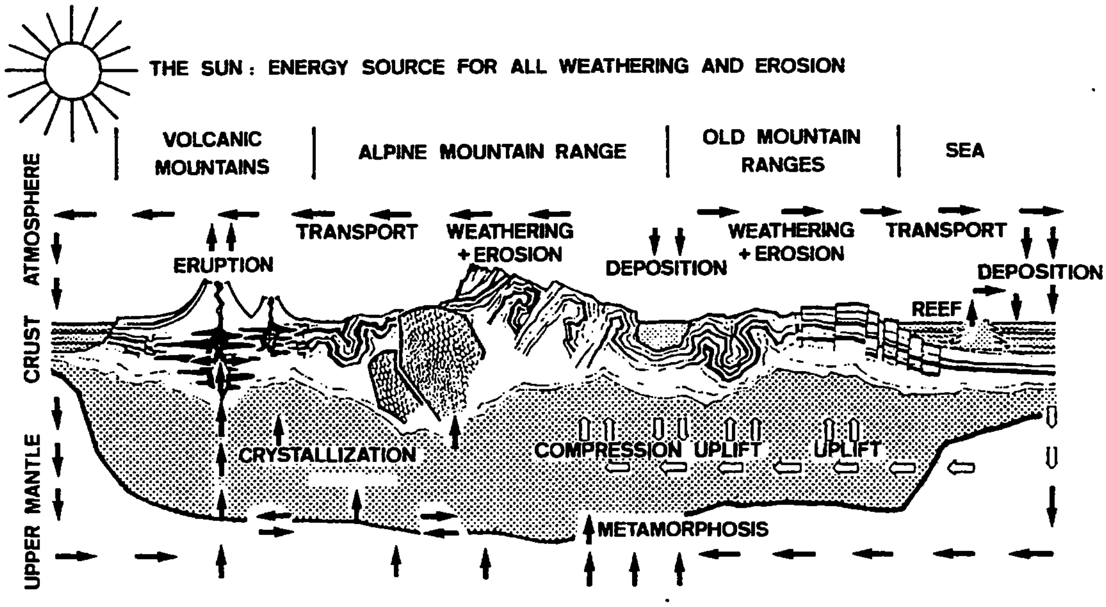
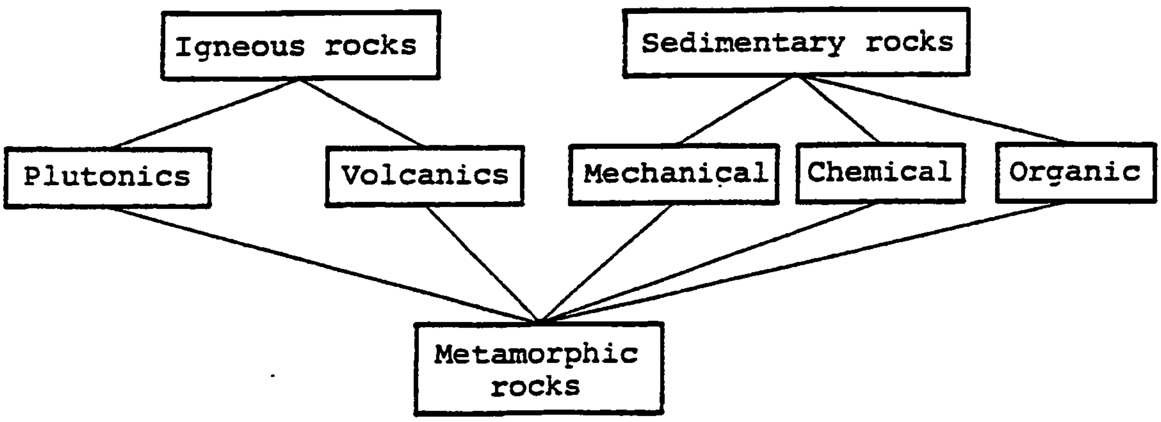


TABLE 7 **Interdependence of rock types**



1.5 Geological Time-Scale

A rock cannot only be classified according to its mineral content and the place of its formation, but also according to its age. The determination of the age of a rock is normally accomplished by palaeontological methods (investigation of the remainders of fossils) or by physical methods (radiocarbon, radio-active decay).

Table 9 shows the worldwide accepted geological terminology regarding the time-scale. Note that limestone being the most important raw material component for the cement industry, has occurred only (in larger quantities) since the beginning of the Paleozoic age.

Note further, that rocks of the same age but from different locations do not necessarily have identical characteristics.

TABLE 9 Geological time scale

Era	System and Period	Series and Epoch	Stage and Duration	Absolute Age
Cenozoic	Quarternary	Recent		Last 10'000 y.
		Pleistocene	1,8 mio	(millions of years ago) 1,8
	Tertiary	Pliocene Miocene Oligocene Eocene Palaeocene	3.2 mio 20 mio 10 mio 20 mio 12 mio	1,8 - 67
Mesozoic	Cretaceous	Upper Lower	73 mio	67 - 140
	Jurassic	Upper Middle Lower	70 mio	140 - 210
	Triassic	Upper Middle Lower	40 mio	210 - 250
Palaeozoic	Permian		40 mio	250 - 290
	Carboniferous		70 mio	290 - 360
	Devonian		50 mio	360 - 410
	Silurian		30 mio	410 - 440
	Ordovician		60 mio	440 - 500
	Cambrian		90 mio	500 - 590
Pre-cambrian	Proterozoic Archean (Oldest rocks)			590 - 2500 (3700)

1.5.1 Chemical Sediments

Chemical sediments are normally formed in sea water where they precipitate under special circumstances due to the ions concentration occurring in sea water. The average ion concentration in sea water are shown in table 11.

TABLE 11

Element	Concentration * in Ocean Water, 10^{-6} g/g	Concentration + in River Water, 10^{-6} g/g	Residence Time, 10^{6} years
Li	0.17		
B	4.6	0.013	15
C	28	11.5	0.1
N	0.5		
F	1.3		
Na	10,500	6.3	71
Mg	1,350	4.1	14
Al	0.01		
Si	3.0	6.1	0.02
P	0.07		
S	885	3.7	10
Cl	19,000	7,8	104
K	380	2,3	7
Ca	400	15	1.15
Mn	0.002	.02	0.004
Fe	0.01	0.7	0.006
Ni	0.002	0.01	0.008
Br	65	0.006-0.019	450-150
Rb	0.12		
Sr	8.0	0.09	3.8
Ag	0.00004	0.001	0.02
I	0.06		
Ba	0.03	0.054	0.02
Pb	0.00003	0.005	0.0003
Th	0.00005		
U	0.003	0.001	0.14

* B. Mason, Principles of Geochemistry (Wiley, 1966, p. 195).
+ D. A. Livingstone (U.S. Geol. Survey Prof. Paper 440-G, 1963)

These ion concentrations are derived from weathering and dissolution processes onshore, e.g. in mountain ranges.

Fig. 5 summarizes the chemical conditions for common sedimentary minerals :

Fig. 5 **Relation of Eh and pH to regions of formation of common sedimentary minerals (after Garrels and Christ)**

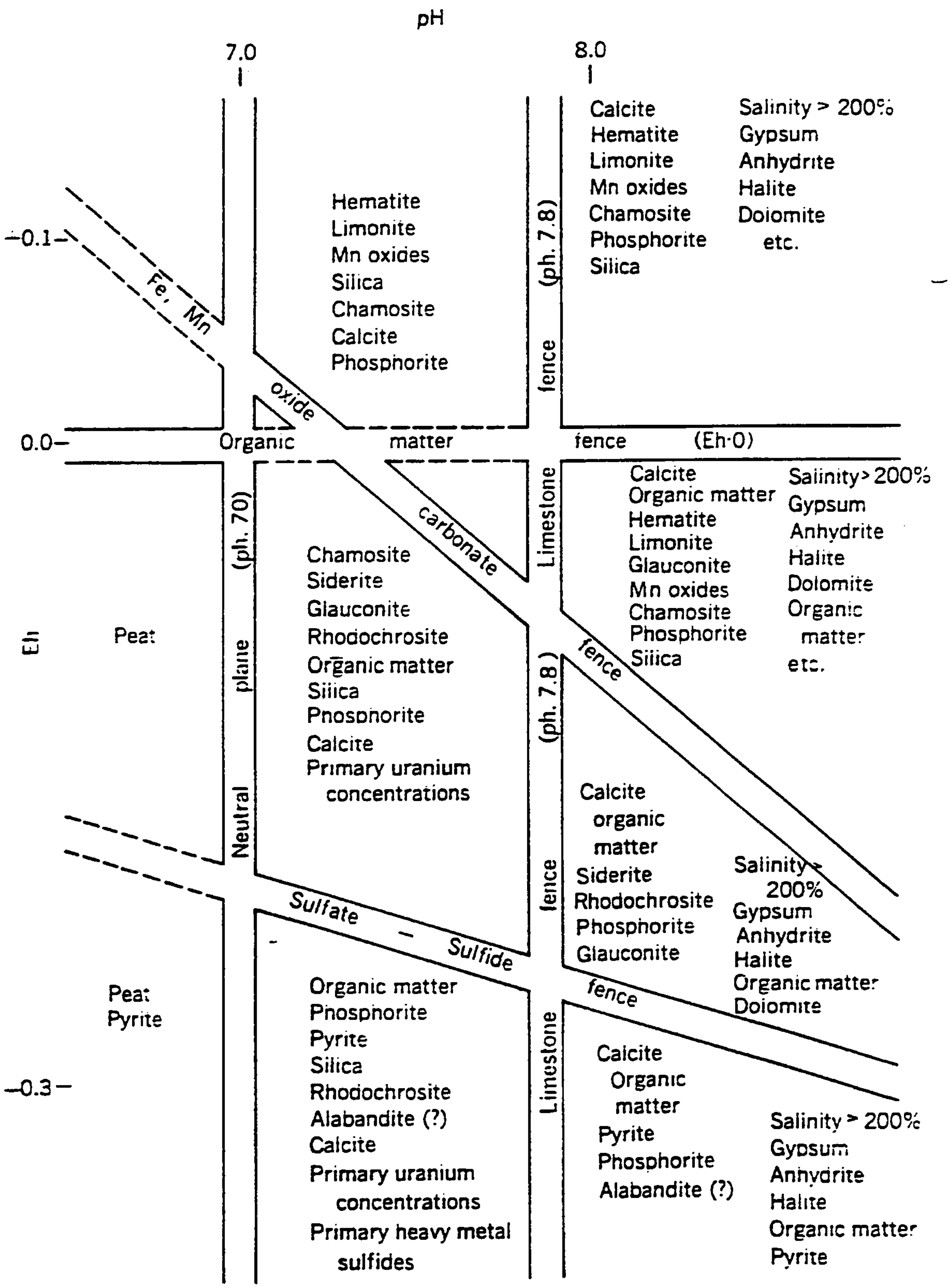
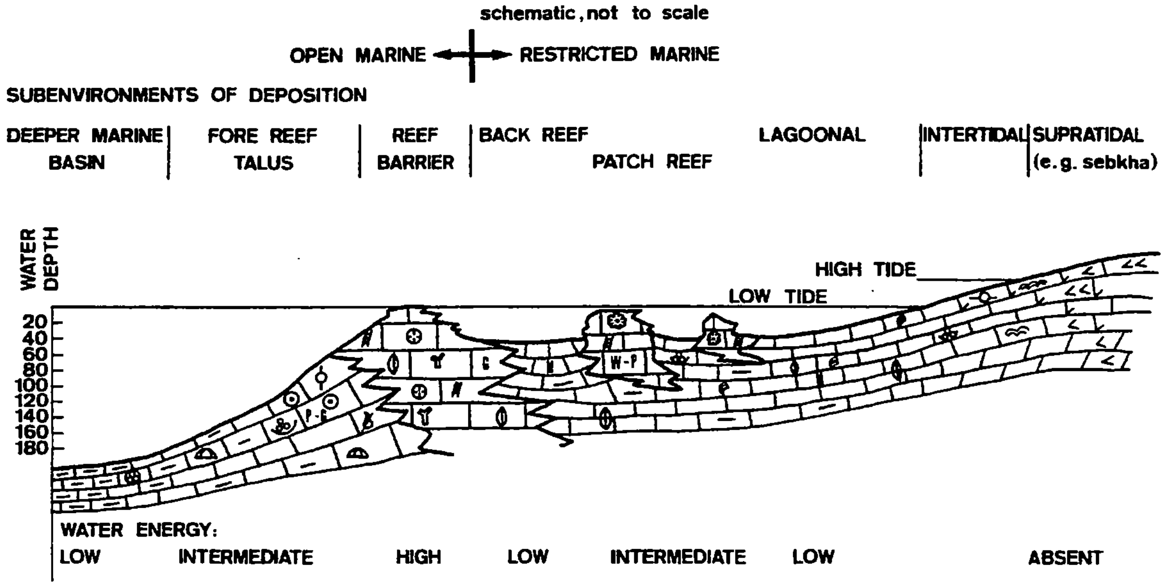


Fig. 5a **General model of a shallow marine carbonate platform**



1.5.2 Shallow marine carbonate platform

The additional presence of H_2CO_3 in seawater (from the air and supplied by river water) allows the formation of $CaCO_3$ under special circumstances. These are governed by a complicated system of chemical reactions:

$$\underset{\text{Solid}}{CaCO_3} \rightarrow \underset{\text{aq}}{Ca^{2}} + \underset{\text{aq}}{CO_3^{2}-}$$

$$\underset{\text{aq}}{CO_3^{2}-} + H_2O \rightarrow \underset{\text{aq}}{HCO_3-} + \underset{\text{aq}}{OH-}$$

$$\underset{\text{aq}}{HCO_3-} + H_2O \rightarrow \underset{\text{aq}}{H_2CO_3} + \underset{\text{aq}}{OH-}$$

$$\underset{\text{gas}}{CO_2} + H_2O \rightarrow \underset{\text{aq}}{H_2CO_3}$$

$$\underset{\text{aq}}{Ca^{2}} + \underset{\text{aq}}{CO_3^{2-}-} \rightarrow \underset{\text{aq}}{CaCO_3}$$

$$\underset{\text{aq}}{Ca^{2+}} + \underset{\text{aq}}{HCO_3^{2}-} \rightarrow \underset{\text{aq}}{CaHCO_3^{+}}$$

$$\underset{\text{aq}}{Ca^{2+}} + \underset{\text{aq}}{SO_4^{2}-} \rightarrow \underset{\text{aq}}{CaSO_4}$$

$$H_2O \rightarrow \underset{\text{aq}}{H^{+}} + \underset{\text{aq}}{OH\ -}$$

The knowledge of chemical equilibrium constants and pH of natural sea water made it possible to calculate carbonate solubilities for various marine environments.

It has been found that in shallow, warm sea waters concentration of $CaCO_3$ is close to saturation. This depends largely on the peculiar behaviour of H_2CO_3, which dissolves calcite when present in higher concentrations and only stimulates $CaCO_3$ precipitation when present in small quantities. This is the case in relatively warm water, where plants additionally remove CO_2, calcite is readily removed by dissolution. Below ~ 4000 m, the so-called "compensation depth", no calcite is normally present.

The preceeding conditions define the environment of deposition for the most important raw materials for cement manufacturing. Located on the so called "shallow marine carbonate platform" or the continental edges. These sites of $CaCO_3$-formation are shallow warm sea water, where organisms like corals, bryozoa, algae etc. form their skeletons (of $CaCO_3$) normally in form of Aragonite.

According to the actualistic theory, it can be assumed that the Bahamas bank, the Arabic Gulf, the Red Sea (sebkha) or the Great Barrier Reef in Australia serve as excellent models for the formation of limestone in shallow warm sea water.

A general model of a shallow marine carbonate platform is shown in fig. 5a. According to water depth, water circulation, water energy (waves), climate, fauna present, a number of subenvironments are discribed. Within these subenvironments a great variety of calcium carbonate particles are produced and deposited. These "soft" carbonate deposits form, after a long time of compaction and diagenesis, a real limestone. Geologists can "read" these different limestones and reconstruct the original environment of deposition of any limestone body.

1.5.3 Limestone diagenesis

All processes in time, which change the physical parameters of limestone, are summarised under this expression. The following points are of interest:

- mechanical compaction due to overburden → reduction of porosity
- recrystallization of aragonite (instable) to calcite, high Mg-calcite (dolomite)
- leaching by rain water or ground water: Early cementation of limestone grains by rapid recrystallization
- chemical compaction by dissolution of calcite and recrystallization in pore spaces
- presence of high Mg-content in pore fluid leads to recrystallization of dolomite → increase of porosity.

Depending on the specific history of a limestone body, diagenesis can produce quite remarkable differences in limestone quality, and often the local changes occur within very short distances. The knowledge of the detailed environment of deposition very often permits a geologic interpretation including an idea as to the spacial distribution of different limestone quantities. Especially important, is the location of dolomitic limestone bodies through reconstruction of the original set of conditions.

Advanced stages of limestone diagenesis are characterized by the absence of porosity, large calcite crystals as developed by progressive recrystallization, pressure solution features like e.g. stylolithes.

The original structure of the limestone is largely destroyed, and it becomes difficult to determine the environment of deposition. Even further diagenesis is called metamophism and leads ultimately to formation of marble.

1.5.4 Classification of limestone

Due to their economic importance, limestone and carbonates in general have been studied in great detail by many researchers and as a consequence, there are many classifications of limestone and related sediments. One of the most widely used was originally conceived by DUNHAM and it describes the relation of lime components of different sizes and origin to the so-called "cement" or "ground mass". Table 12 gives an impression of the various limestone types and related names. This classification allows an adequate description of limestone in terms of environment of deposition, but it differs greatly from the classification of the clastic sediments.

TABLE 12: Carbonate textural classification (Dunham, slightly modified)

<table>
<tr><th colspan="4">TEXTURE</th><th rowspan="2">NAME</th><th colspan="2">ABBREVIATION</th></tr>
<tr><td rowspan="6">Depositional texture reconizable</td><td colspan="3">*) Original components bound together during deposition</td><td>informal</td><td>computer</td></tr>
<tr><td rowspan="6">*)
"</td><td rowspan="2">Grain supported</td><td>Locks Mud</td><td>Lime-Boundstone</td><td>Bdst</td><td>B</td></tr>
<tr><td>Contains Mud</td><td>Lime-Grainstone</td><td>Grst</td><td>G</td></tr>
<tr><td rowspan="4">Mud-suported</td><td rowspan="4">Particles (> 20µ)
> 10 %

< 10%</td><td>Lime-Packstone</td><td>Pkst</td><td>P</td></tr>
<tr><td>Lime-Wackestone</td><td>Wkst</td><td>W</td></tr>
<tr><td>Lime-Mudstone</td><td>Mdst</td><td>M</td></tr>
<tr><td>............</td><td>aphanitic</td><td>aph</td><td>A</td></tr>
<tr><td>............</td><td colspan="2" rowspan="2">Recrystallized texture</td><td>Fine</td><td>crystalline</td><td>xin</td><td>X</td></tr>
<tr><td>Depositional texture not recognizable</td><td>Coarse</td><td>sucrosic</td><td>suc</td><td>S</td></tr>
</table>

1.5.5 Clastic sediments

Clastic or "mechanical" sediments are formed from solid particles which are transported from areas of erosion to areas of deposition. The transport agent can be water, wind or ice, the most common being water. Coarse particles require high water energy for transport, normally linked to a steep topographic gradient, to be removed from their place of origin. During transport they are further fragmented, chemically altered and mechanically shaped. The end product, the clastic sediment, therefore depends on a variety of parameters, but mainly on:

- energy of transporting agent, defining in turn
  - grain size distribution
  - shape of grains or "clasts"
- time of transport, influencing chemical composition of particles, sorting of grains according to size and quality
- nature of originally eroded rocks, which defined to a large extent what type of particles are formed. In a rock with little chemical resistance very small particles are formed from partly altered minerals, the clay minerals.

The complex cycle of erosion - transport - deposition results in a separation of the particles and this is expressed with the term "maturity" of a clastic sediment. Long transport distance

and time leads to the deposition of the most resistant particles in uniform grain size distribution and well rounded like a pure quartz sandstone. Short transport distance and time produces e.g. a breccia or conglomerate with large components of heterogeneous mineralogical composition.

Fig. 5b Clasical environment of "mechanical" or clastic deposition

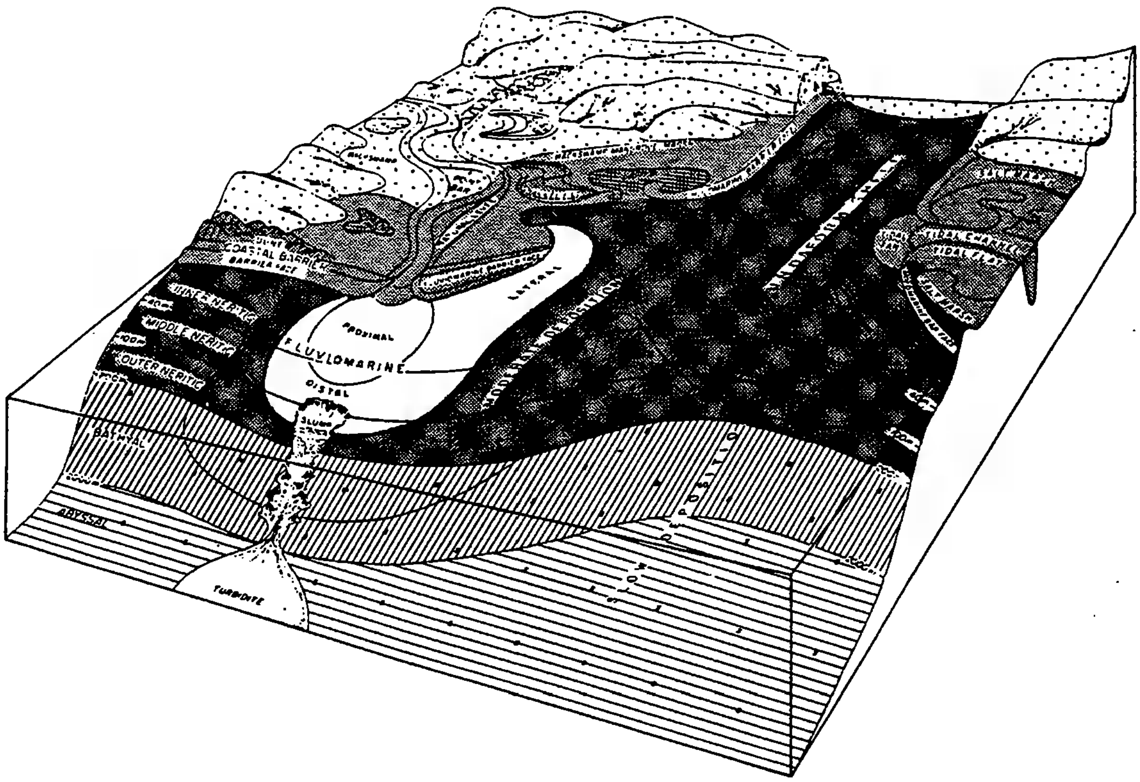


Fig. 5b Legend

LEGEND:

CONTINENTAL ENVIRONMENTS

FLUVIATILE ENVIRONMENT

- BRAIDED RIVER
- MEANDERING RIVER
- ALLUVIAL FANS

LACUSTRINE ENVIRONMENT

DESERT ENVIRONMENT

- DUNES
- WADI DEPOSITS

GLACIAL ENVIRONMENT

COASTAL OR „TRANSITIONAL MARINE" ENVIRONMENTS

DELTAIC ENVIRONMENT

SHALLOW SHELF ENVIRONMENT

INTERTIDAL ENVIRONMENT

COASTAL BARRIER ENVIRONMENT

EVAPORITIC ENVIRONMENT

HOLOMARINE ENVIRONMENTS

NERITIC ENVIRONMENT

BATHYAL ENVIRONMENT

ABYSSAL ENVIRONMENT

1.5.6 Clastic environments of deposition

Inevitably, the clastic particles are formed on the continents, transported and ultimately end up in the oceans. A summary of the most important environments of clastic deposition is given in Fig. 5b.

The dominant factors in forming the specific sedimentary features of clastic environments is documented further in Figs. 5c, 5d, 5e, 5f and 5g. Three important environments, delta, coastal barrier and deep sea fans, each of which is characterised by very distinct sedimentary structures, fossils and trace fossils.

Delta Environment

Fig.5c **Schematic Diagram of Delta**

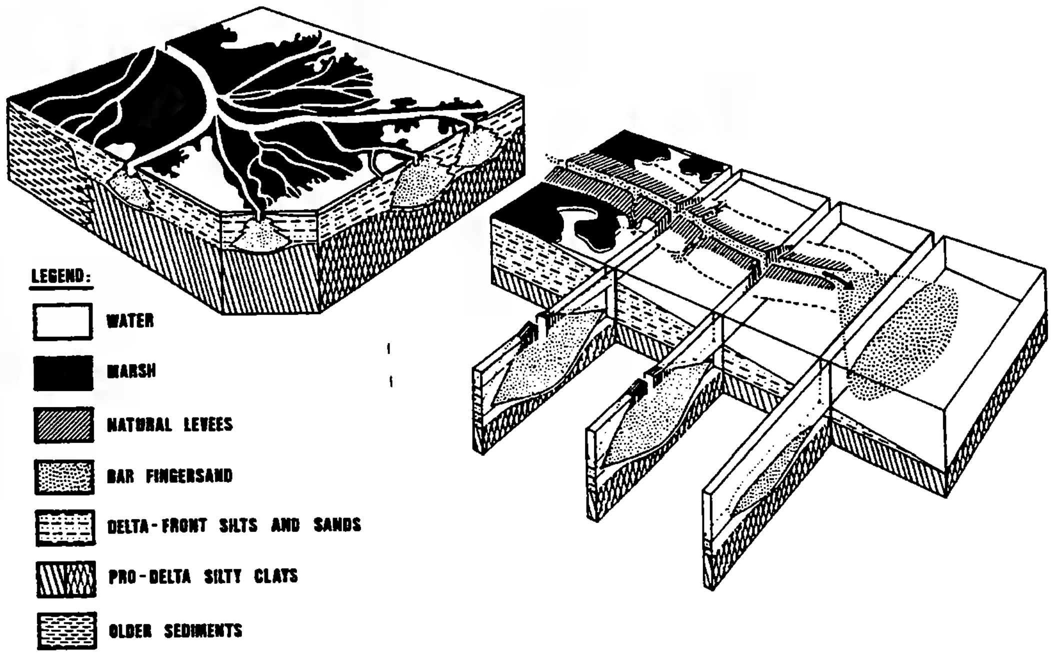
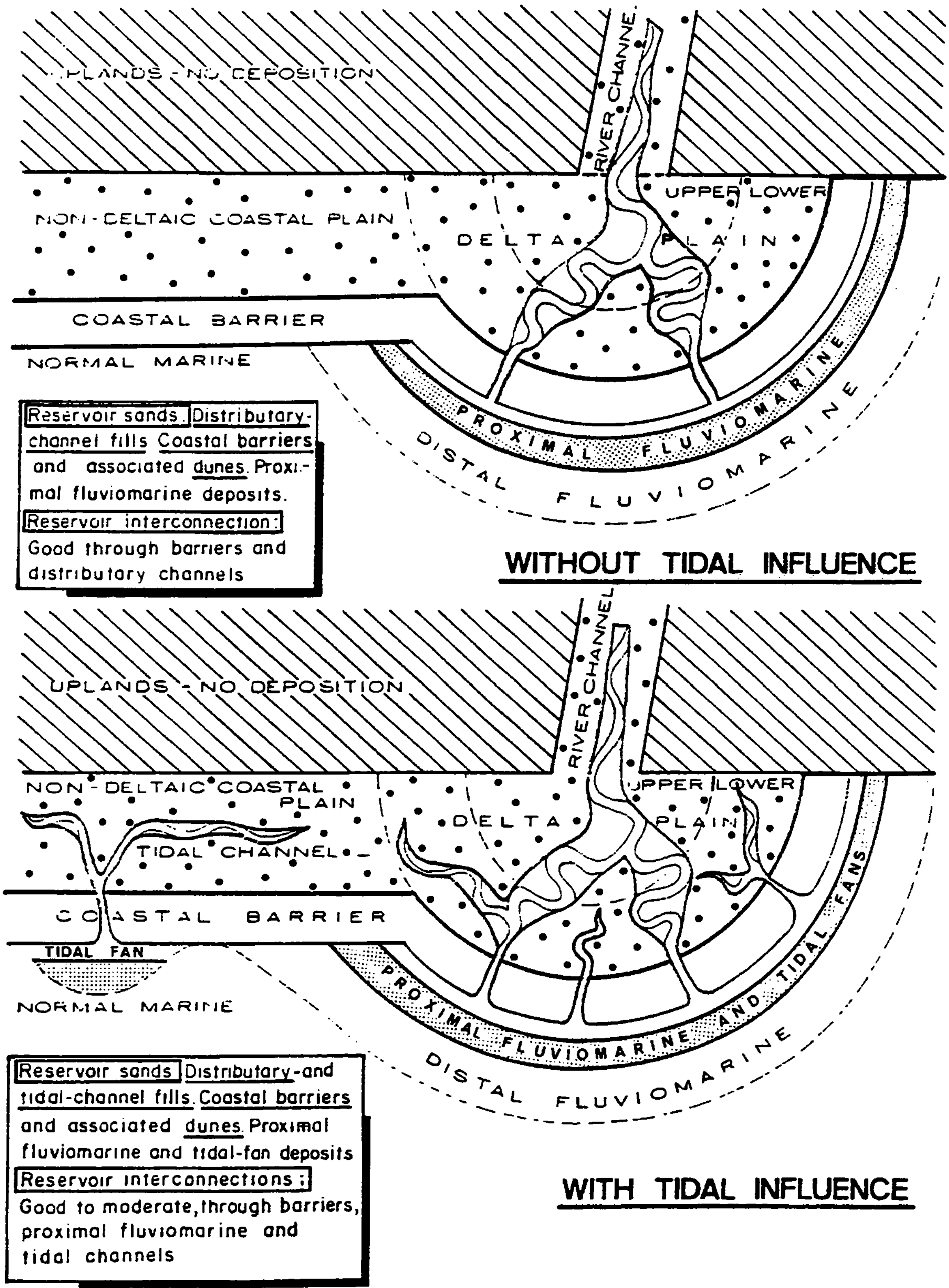


Fig.5d **Wave Dominated Deltas**



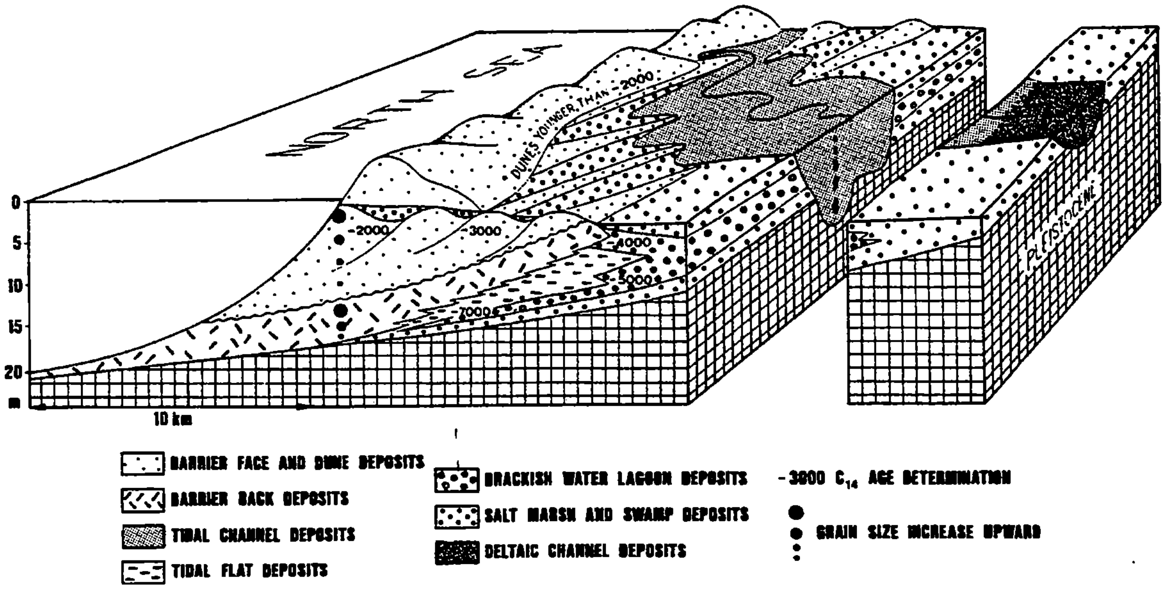
WAVE - DOMINATED DELTAS

CHARATERISTIC: Slow seaward growth, leaving waves time to rework fluviomarine deposits into coastal barriers

Sub environment	Type of particles deposited	Sedimentary features bedding	Contents of fauna / flora
natural levee	silty clay	laminated root disrupted current ripples	plants
marsh, swamps	silty clay, peat	no bedding Burrows	plants
channel fill	sand	cross bedding clay balls	(plants)
distributory channel	sand	cross bedding current ripples clay balls	nearly absent
mouth bar	sand, silt	trough cross bedding, wave + current ripples gas heave structures	nearly absent
distal bar	silt, clay	cross bedding ripples burrows	dense benthonic fauna
pro delta (delta front slope)	clay, silty clay	lamination ripples graded bedding bioturbation	benthonic fauna

Coastal barrier environment

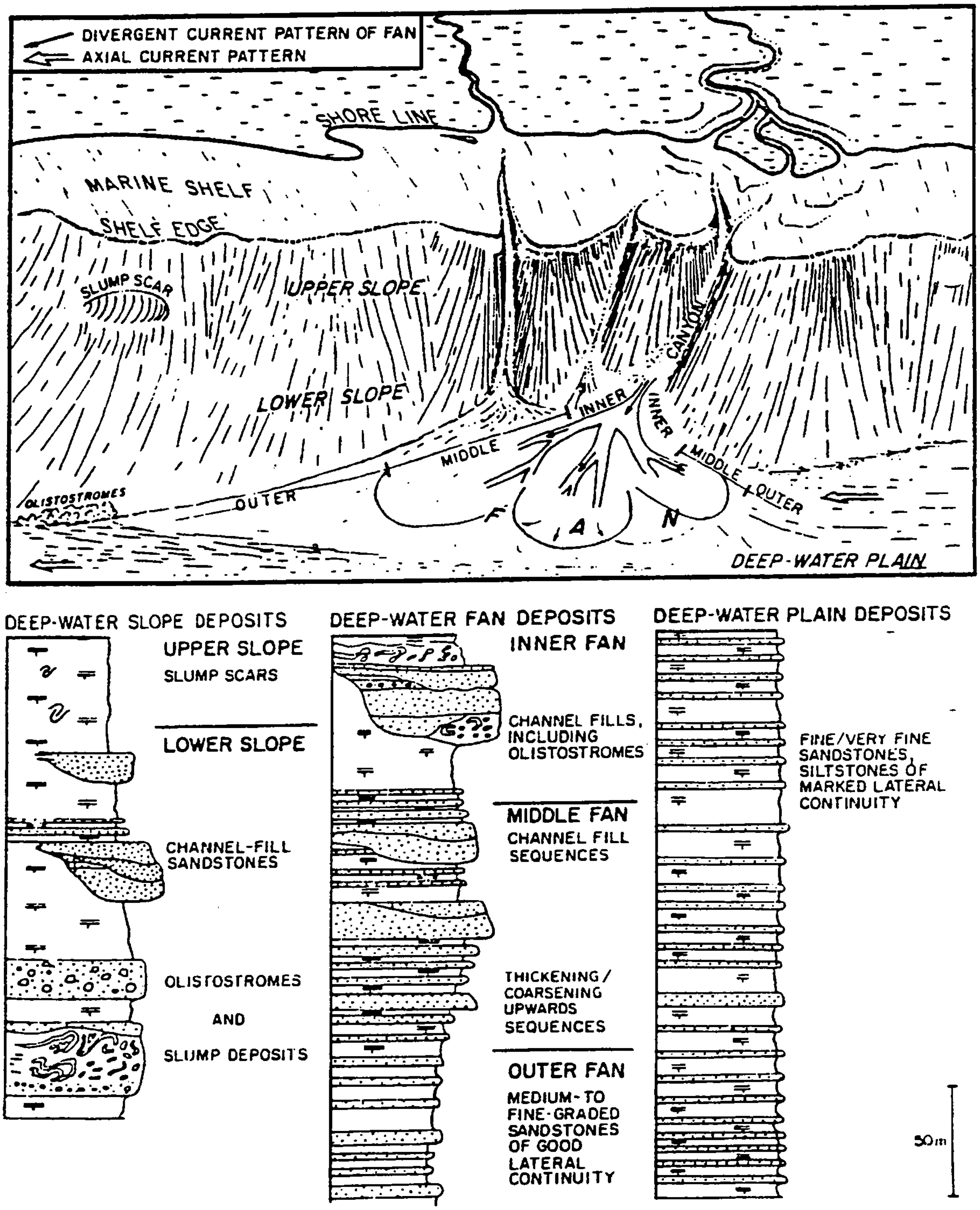
Fig. 5e Holocene Coastal Plain Deposits



The dominant energy source is waves, the tide and long shore currents. Particles are extensively reworked and rearranged, refer Fig. 5e. Note the occurrence of dunes which depend also on wind transport. According to climate, tide differences, material supply and vegetation, many variations of the presented model may occur.

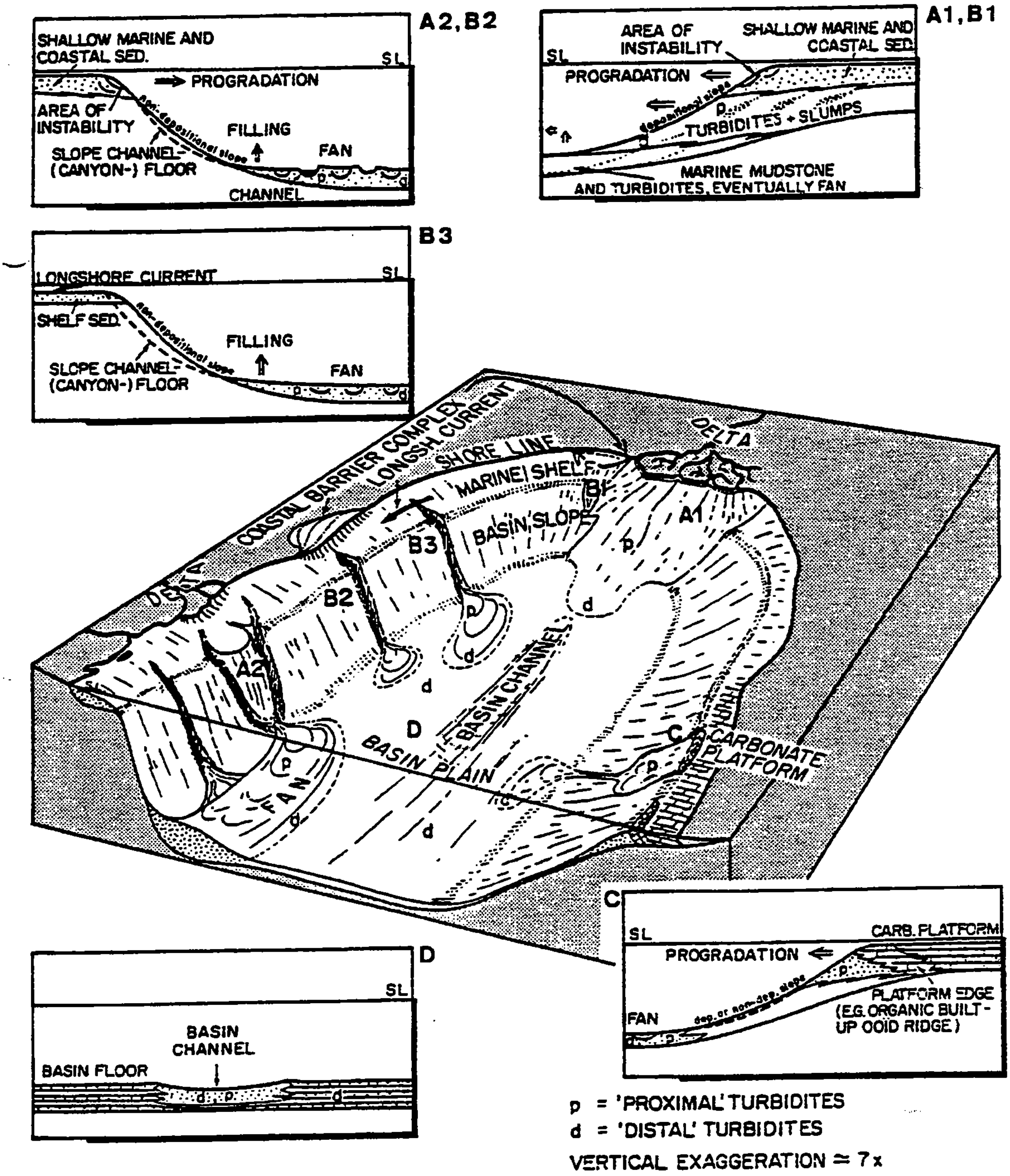
Deep sea fan (bathyal to abyssal environment)

Fig. 5f Subaqueous fan and lithological columns of various fan deposits



A MODEL OF DEEP-WATER SLOPE AND FAN DEPOSITION

Fig. 5g Integrated model of deep-water sand distribution



Deep sea fans are formed by means of a special transport mechanism called "turbidity current". Unconsolidated particles which are deposited on the shelf edge may become unstable and start to flow downwards in form of an high density aquatic suspension. These carry large masses of sediments down the continental slope and spread in the deep marine basins over large areas (thousands of km^2). During settling of the particles, typical "graded bedding" develops.In addition to which various other sedimentary features such as flue casts, parallel lamination, current ripple lamination, convolute bedding and pelitic (clay) layers.

Turbidity currents, which are triggered by earthquakes, occur frequently - about every 10'000 years under favorable circumstances. These form a single bed, nearly instantaneously. During the intervening time period, between consecutive turbidity currents, the normal "pelagic" deposition of clay and lime particles continues. This covers the top of the turbidite layer with a relatively thin layer which contains normally datable "nannoplankton" (remnants of calcareous algae floating at the surface of the open ocean). Turbidite sequences are extremely well bedded and exhibit normal characteristic alternations of sand and clay or limestone and clay, depending on the origin of the particles. They can represent a perfect natural raw mix for cement manufacturing.

1.5.7 Classification of clastic sediments

Determining factors for a classification are not only genetic features, as outlined above, like

- specific environment of deposition
- sedimentary features
- fauna/flora content

but also parameters which can be measured objectively and are of technical relevance like

- grain size distribution
- chemical composition
- mineralogical composition
- degree of consolidation
- porosity, permeability

Tables 13 and 14 give two examples of the classification on the basis of grain size distribution, considering well sorted clastic sediments.

TABLE 13: Classification of mechanical sediments

Grain size (mm)	Constituents	Degree of Consolidation	
		loose	solid
> 200	boulders, blocks		
200-20 20-2	coarse gravel) fine gravel) psephite	rubble	breccia conglomerate
2-0.2 0.2- 0.02	coarse sand fine sand) psammite	sand	sandstone
0.02-0.002 < 0.002	clay silt) colloidal clay) pelite	clay	claystone

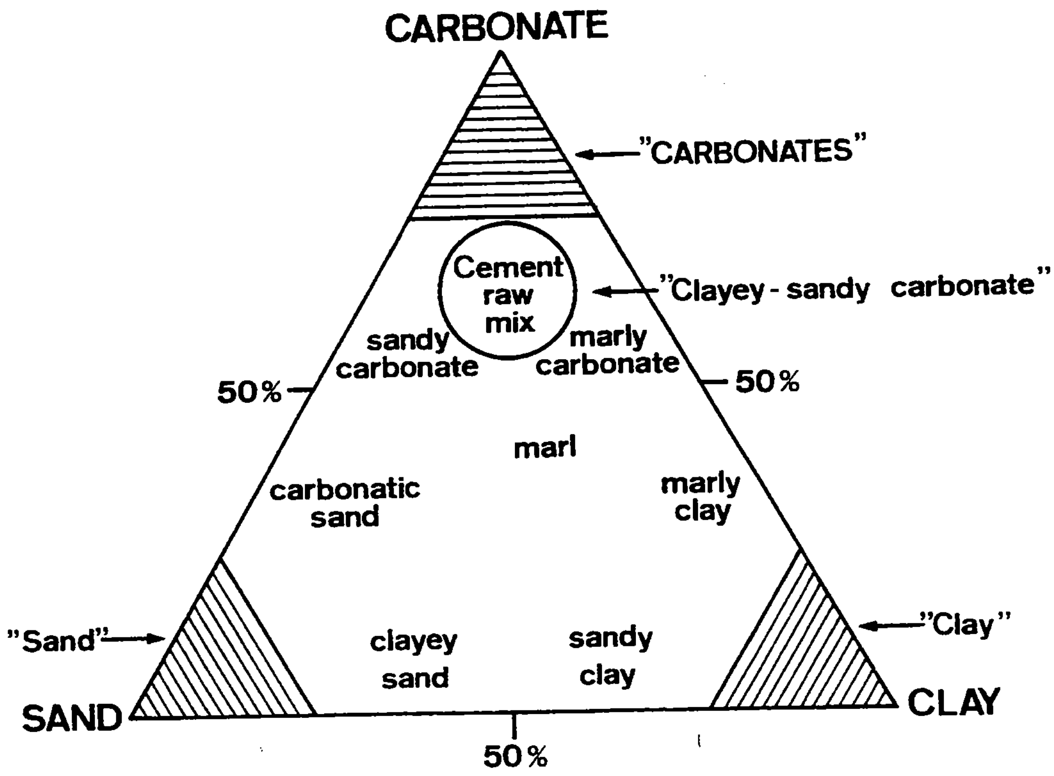
TABLE 14: Definition of grain size

Subclass	Class	Limit	Scale
	COBBLE		
		63mm	63mm
VERY COARSE	GRAVEL		
			32
COARSE	GRAVEL	20	
			16
MEDIUM	GRAVEL		
			8
FINE	GRAVEL	5,3	
			4
VERY FINE	GRAVEL		
		2mm	2000 µ
VERY COARSE	SAND		
			1000
COARSE	SAND	0,63	
			500
MEDIUM	SAND		
			250
FINE	SAND	0,2	
			125
VERY FINE	SAND		
		0,053	63
VERY COARSE	SILT		
			32
COARSE	SILT	0,02	
			16
MEDIUM	SILT		
			8
FINE	SILT	0,0053	
			4
VERY FINE	SILT		
		0,002	2
	CLAY		

1.5.8 Mixtures of Clastic and Chemical Particles

Since most of the natural sedimentary rocks are mixes of various types of rock, classification thereof can also be accomplished with a three-component diagram (Fig. 6).

Fig. 6 **Display of the definitions of rock types in the sand-clay-carbonate-system**



Sandy-clayey-marly rocks are also designated as "siliceous" rocks; sandy-clayey materials as "argillaceous" rocks. In addition, the term carbonatic can be replaced by "calcareous".

As a further example (Table 15), the carbonatic (or calcareous) rocks are selected to illustrate the principle of classification based on chemical characteristics.

TABLE 15 **Classification of calcareous and clayey materials (according to HMC's practice)**

$CaCO_3$ %	Clay minerals %	Nomenclature
100 - 95	0 - 5	high-grade limestone
95 - 85	5 - 15	limestone
75 - 85	15 - 25	marly limestone
65 - 75	25 - 35	calcareous marl
35 - 65	35 - 65	marl
25 - 35	65 - 75	clayey marl
15 - 25	75 - 85	marly clay
5 - 15	85 - 95	clay
0 - 5	95 - 100	high-grade clay

The same principles may be applied to the group of calcareous-siliceous (sandy) materials and the group of siliceous and clayey rocks.

1.6 Structural geology

Structural geology deals with the deformation of rocks. This deformation is a result of tectonic (mechanical) forces, which occur in the solid lithosphere due to movements of the continental plates. In detail, a stressfield applied on the rock formations results in deformation in form of rupture in the case of brittle deformation or flow in case of plastic deformation. These stressfield forces are very large and act over long time periods. In the case of brittle deformation, the theoretical approach by means of physical - mathematical methods is not too complex. However, as soon as plastic deformation over a long period of time is also considered the analytical approach becomes very complicated. The study of the phenomena of rock deformation is known as "tectonics." A science, which incorporates higher mathematics.and physics.

In our industry the structural behaviour and characteristics of the raw material deposits is of high interest, since it has an important impact on the distribution of rock qualities within the deposits. For the description of deformation, one requires a reference system, which shows the effect of deformation with regard to an original, undeformed situation. One very common system is stratification, a frequently observed sedimentary feature. In it's original state stratification is practically horizontal, due to the gravity forces. If strata are found in inclined position in the field, a deformation phase is normally responsible.

By measuring the inclined position of bedding planes, fault planes, joint surfaces, inclination and orientation of folds etc. the degree and type of deformation can be determined.

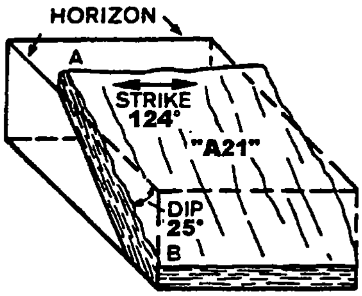
The corresponding measurements are called strike and dip. For example, in order to measure the orientation and inclination (strike and dip) of a bedding plane (refer figure 8). The intersection of the inclined bedding plane and an imaginary horizontal plane (water line) represents a straight line in space. This line or 'strike direction' has an astronomical orientation, which is measured, with a compass, in degrees clockwise from the (Azimuth).

The inclination, or 'dip', of the bedding plane is measured along a line perpendicular to the strike direction. The dip angle is measured with an inlinometer in degrees with respect to the horizontal plane. There are normally two solutions for this dip angle depending on the orientation 'strike' of the bedding plane ie. dipping in a N or S direction.

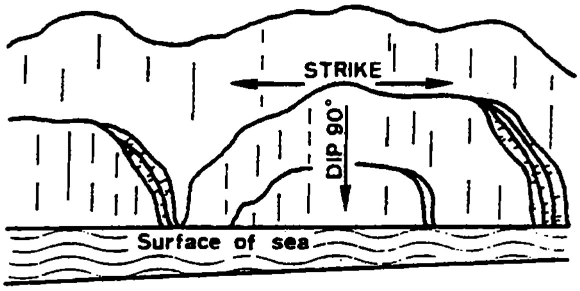
A complete measurement of strike and dip of a bedding plane at the locality (or position) A21 would be "A21 - 124 / 25° N". There are various conventions in different countries for recording these measurements. In the USA the dip direction is very often given in form of an azimuth reading such that the above reading would be "A21 - 034 / 24°."

By means of these measurements it is often possible to define the type and intensity of rock deformation and therefore work out the "tectonic style" of a given raw material deposit. In the case of geologic faults, three main fault types are defined, based on the orientation of the three main stress axis of the applied stressfield ($Ó_1$, $Ó_2$ and $Ó_3$, whereby $Ó_1 > Ó_2 > Ó_3$) (Fig. 9):

Fig. 8 Strike and Dip Measurements

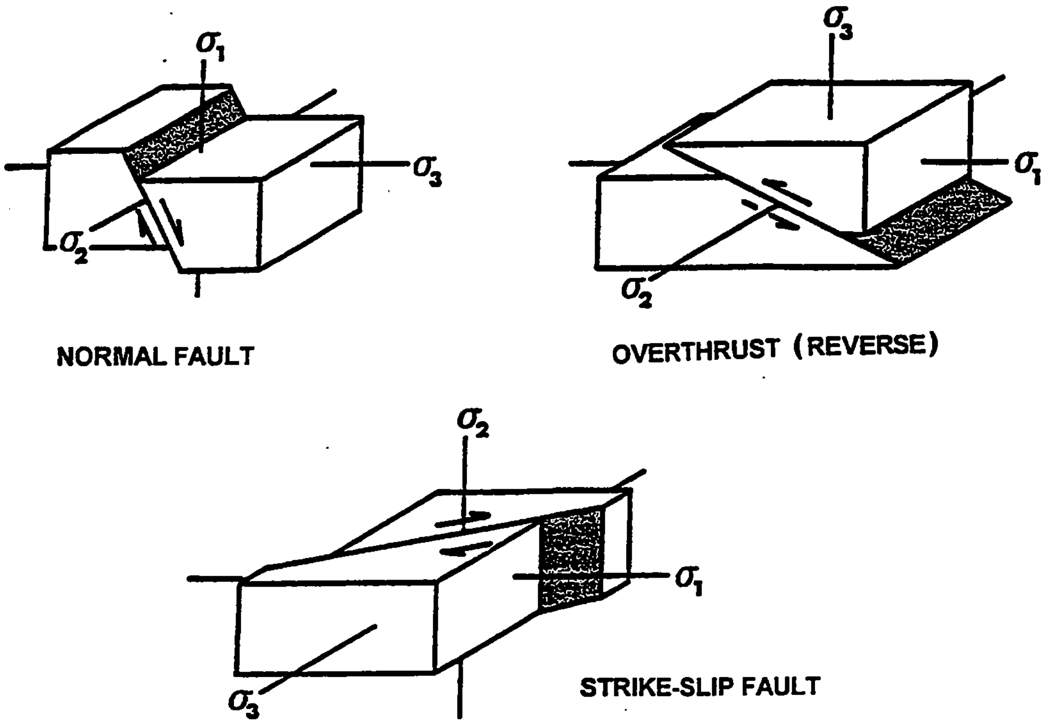


Strike and Dip



- Ó$_1$ vertical, Ó$_2$ and Ó$_3$ horizontal: the gravity becomes the largest force and therefore blocks of rock glide downward along typically inclined faults of 60°. These faults are called normal faults. They are typical for extensional tectonics.
- Ó$_1$ and Ó$_2$ horizontal, Ó$_3$ vertical: This situation represents a compressional regime, where the rock body is shortened by overthrusts and or folds. Typically, the fault planes are inclined 30° with respect to the horizontal plane.
- Ó$_1$ and Ó$_3$ horizontal, Ó$_2$ vertical: The result of this configuration is the so called strike-slip faults (or wrench faults) which are generally vertical and indicate a strike which deviates 30° from the Ó$_1$ direction.

Fig. 9 **Classic Geologic Fault Types**



σ_1 main stress σ_2 intermediate stress

σ_3 lowest stress

In nature, these clear-cut cases are seldom found. Fault zones are mostly accompanied by secondary faults and by a pattern of "joints" (small fractures).

Combination of fault types and repetitions thereof are frequently found, e.g. series of normal faults, series of overthrusts and folds etc.

In case of folding, the variability of structures produced is also bewildering (see fig 10): depending on the geology of the rocks involved and the stress forces applied, a wide range of different of folds types develop.

Fig. 10 Classic Fold Types

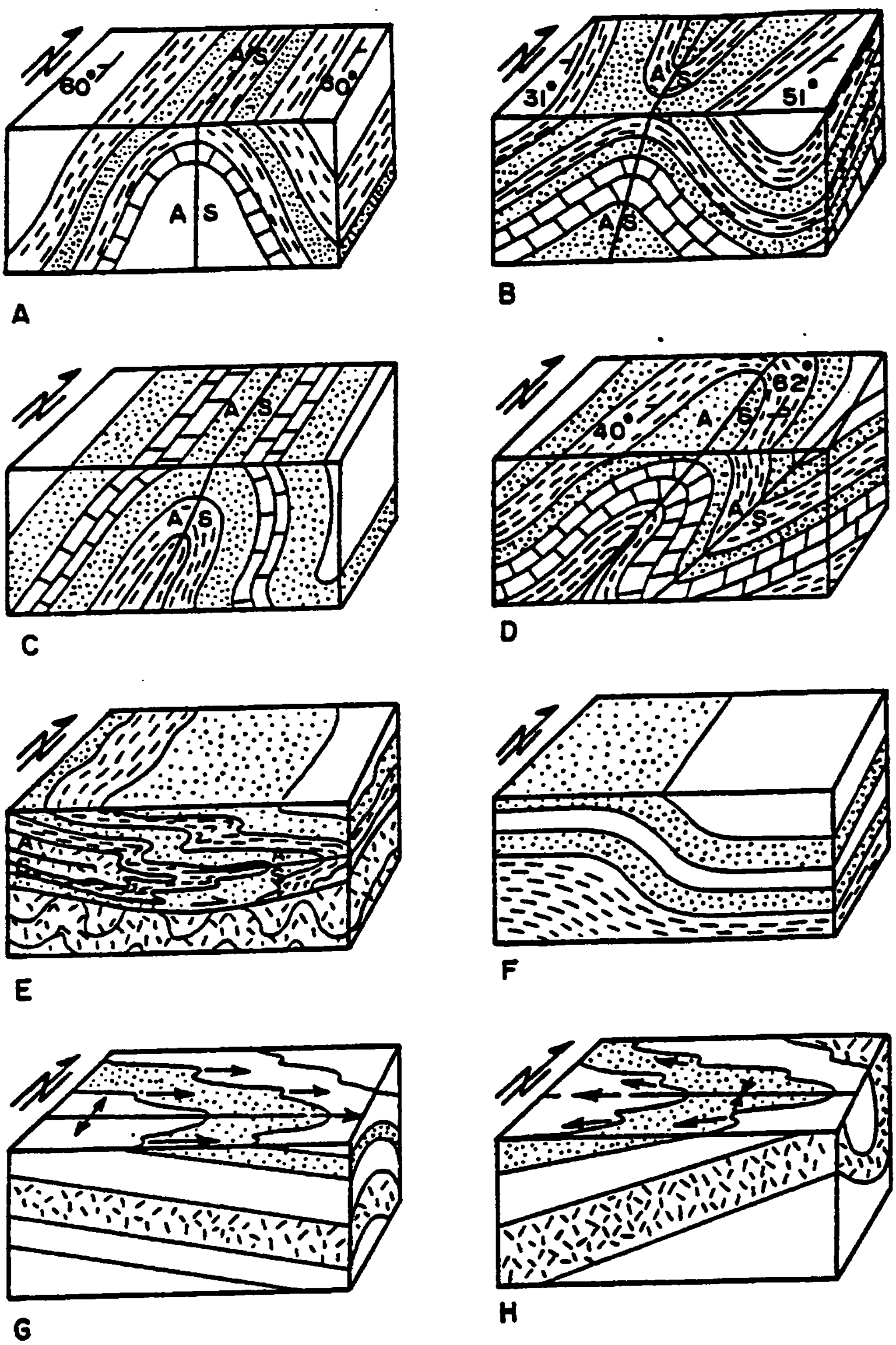
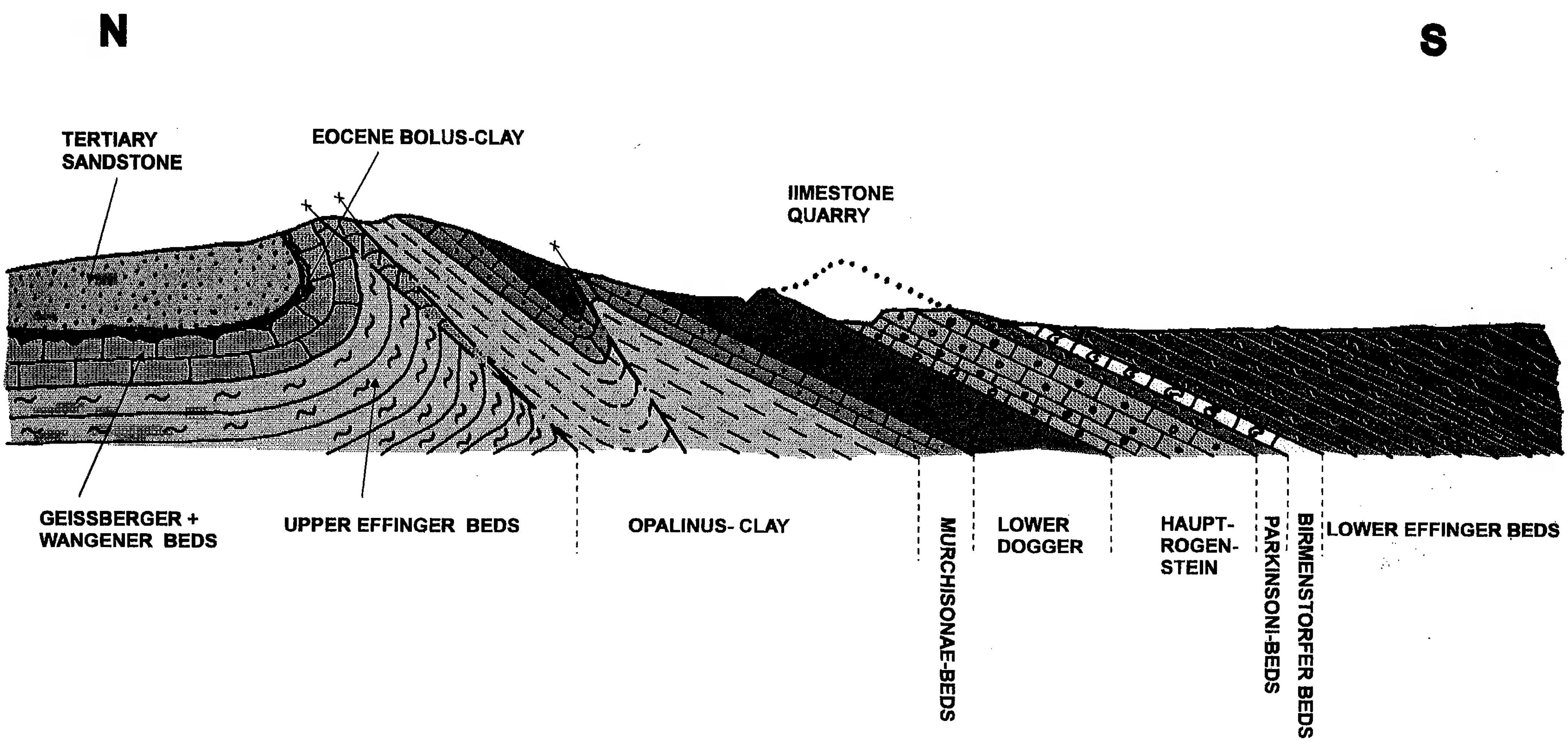


Fig. 10 (A) Symmetrical, open, nonplunging anticline, showing the position of the axial surface (AS). (B) Asymmetrical south-plunging folds showing the position of the axial surface (AS) in the anticline. In this case the axial surface to the west. (C) Isoclinal, nonplunging, closed, inclined fold. (D) Overturned north-plunging fold. Overturning is to the east. The axial surfaces (AS) dip west-ward. (E) Recumbent, nonplunging fold. The axial surface is essentially horizontal. Sometimes referred to as "nappe structures," although the

underlying limb is not always present (e.g., Austro-Alpine nappes). (F) Monocline. (G) Cylindrical, east-plunging anticline. (H) Conical, west-plunging syncline. The plunge symbols diverge from a vertex located near the east edge of the diagram.

GEOLOGICAL CROSS-SECTION
GISLIFLUH ANTICLINE

SCALE 1:5000, HOR.+VERT.



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